CONTROLLING THE PRODUCTION OF A LIQUEFIED NATURAL GAS PRODUCT STREAM

The present invention relates to controlling the production of a liquefied natural gas product stream obtained by removing heat from natural gas in a heat exchanger, wherein the natural gas passes through one set

5   of tubes located in the shell side of the heat exchanger. In the heat exchanger, the natural gas is in indirect heat exchange with expanded heavy mixed refrigerant and expanded light mixed refrigerant. The heavy mixed refrigerant and the light mixed refrigerant circulate in

10   a closed refrigeration cycle, which includes the shell side of the heat exchanger, a compressor, a cooler, a separator, two additional sets of tubes in the heat exchanger and two expansion devices debouching into the shell side, wherein the heavy mixed refrigerant and the

15   light mixed refrigerants are produced as the liquid product and the vapour product from the separator, respectively. In the shell side of the heat exchanger, the expanded heavy mixed refrigerant and the expanded light mixed refrigerants are allowed to evaporate so as

20   to remove heat from the natural gas passing through the one set of tubes and from the heavy and light mixed refrigerant passing through the two additional sets of tubes in the heat exchanger.

The heat exchanger can be a spoolwound heat exchanger

25   or a plate fin heat exchanger. In the specification and in the claims the term shell side is used to refer to the cold side of the heat exchanger and the terms tube and tube bundle are used to refer to the warm side of the heat exchanger.

European patent application publication No. 893 665 discloses in Figures 4 and 5 a method of controlling the production of a liquefied natural gas product stream, which method comprises the steps of:

5 a) measuring the flow rate and the temperature of the liquefied natural gas, and measuring the flow rates of the heavy mixed refrigerant and of the light mixed refrigerant;

b) maintaining the flow rate of the liquefied natural
10 gas product stream at an operator manipulated set point and maintaining the temperature of the liquefied natural gas product stream at an operator manipulated set point, wherein maintaining the temperature of the liquefied natural gas product stream at its operator manipulated
15 set point comprises the steps of:

b1) determining a dependent set point for the total mixed refrigerant flow rate, the dependent set point being the sum of (i) an incremental change of the flow rate of the total mixed refrigerant to offset a difference between
20 the temperature of the liquefied natural gas product stream and the operator manipulated set point for the temperature and (ii) the product of the operator manipulated set point for the flow rate of the liquefied natural gas product stream and the ratio of the flow rate
25 of the total mixed refrigerant to the flow rate of the liquefied natural gas product stream (which ratio has a given value);

b2) determining a dependent set point for the light mixed refrigerant flow rate that is equal to the dependent set
30 point for the flow rate of the total mixed refrigerant divided by the sum of 1 (= unity) and the operator manipulated set point for the ratio of the flow rate of the light mixed refrigerant to the flow rate of the heavy mixed refrigerant, and determining a dependent set point
35 for the heavy mixed refrigerant that is the difference

between the dependent set point for the flow rate of the
total mixed refrigerant and the dependent set point for
the light mixed refrigerant flow rate; and
b3) maintaining the light mixed refrigerant flow rate and
the heavy mixed refrigerant flow rate at their dependent
set points.

In this method the flow rate of the liquefied natural
gas product stream and its temperature are independently
controlled, and the flow rate of the total mixed
refrigerant is a dependent variable. As a consequence,
the maximum available power from the turbines that drive
the compressors cannot be fully utilized.

It is therefore an object of the present invention to
provide a method of controlling the production of a
liquefied natural gas product stream wherein the
temperature of the liquefied natural gas product stream
and the flow rate of the mixed refrigerant are
controlled, such that the flow rate of the liquefied
natural gas product stream is a dependent variable.

To this end the method of controlling the production
of a liquefied natural gas product stream obtained by
removing heat from natural gas in a heat exchanger in
which the natural gas is in indirect heat exchange with
expanded heavy mixed refrigerant and expanded light mixed
refrigerant according to the present invention comprises
the steps of:
a)   measuring the temperature and the flow rate of the
liquefied natural gas product stream and measuring the
flow rates of the heavy mixed refrigerant and of the
light mixed refrigerant;
b)   selecting the flow rate of one of the refrigerants
(the heavy mixed refrigerant, the light mixed refrigerant
or the total mixed refrigerant) to have an operator
manipulated set point, and generating a first output
signal for adjusting the flow rate of the heavy mixed

refrigerant and a second output signal for adjusting the flow rate of the light mixed refrigerant using (i) the operator manipulated set point for the flow rate of the one of the refrigerants, (ii) the flow rates of the heavy and light mixed refrigerants and (iii) an operator manipulated set point for the ratio of the flow rate of the heavy mixed refrigerant to the flow rate of the light mixed refrigerant;

c)   adjusting the flow rates of the heavy mixed refrigerant and the light mixed refrigerant in accordance with the first and second output signals;

d)   determining a dependent set point for the ratio of the flow rate of the liquefied natural gas product stream to the flow rate of one of the refrigerants such that the temperature of the liquefied natural gas product stream is maintained at an operator manipulated set point, and determining a dependent set point for the flow rate of the liquefied natural gas product stream using (i) the dependent set point for the ratio of the flow rate of the liquefied natural gas product stream to the flow rate of the one of the refrigerants and (ii) the flow rate of the one of the refrigerants; and

e)   maintaining the flow rate of the liquefied natural gas product stream at its dependent set point.

The method of the present invention permits continuous maximum utilization of the available power to drive the compressors in the refrigeration cycle, because the operator can manipulate the set point of the flow rate of one of the refrigerants and the ratio of the flow rates of the heavy mixed refrigerant to the light mixed refrigerant.

The invention will now be described by way of example in more detail with reference to the accompanying drawings, wherein

Figure 1 shows schematically a flow scheme of a
liquefaction plant provided with means for carrying out
the present invention;

Figure 2 shows schematically an alternative control
5   for the liquefied natural gas product stream; and

Figure 3 shows schematically an alternative
embodiment of the invention.

Reference is now made to Figure 1. The plant for
liquefying natural gas comprises a heat exchanger 2
10   having a shell side 5. In the shell side are arranged
three tube bundles 7, 10 and 11. The plant further
comprises a compressor 15 driven by a suitable driver 16,
a refrigerant cooler 18 and a separator 20.

During normal operation, natural gas is supplied at
15   liquefaction pressure through conduit 30 to the first
tube bundle 7 in the heat exchanger 2. The natural gas
flowing through the first tube bundle 7 is cooled,
liquefied and sub-cooled. The sub-cooled liquefied
natural gas flows out of the heat exchanger 2 through
20   conduit 31. The conduit 31 is provided with an expansion
device in the form of a flow control valve 33 (optionally
preceded by an expansion turbine, not shown) to control
the flow rate of the liquefied natural gas product stream
and to allow storing of the liquefied natural gas product
25   stream at about atmospheric pressure.

Mixed refrigerant used to remove heat from the
natural gas in the heat exchanger 2 circulates through a
closed refrigeration cycle. The closed refrigeration
cycle includes the shell side 5 of the heat exchanger 2,
30   conduit 40, the compressor 15, conduit 41, the cooler 18
arranged in the conduit 41, the separator 20, conduits 42
and 43, the two tube bundles 10, 11 in the heat
exchanger 2, and conduits 44 and 45 debouching into the
shell side 5. The conduits 44 and 45 are provided with
35   expansion devices in the form of flow control valves 46

and 47. The flow control valves 46 and 47 can optionally
be preceded by an expansion turbine, not shown.

The gaseous refrigerant, which flows from the shell
side 5 of the heat exchanger 2 is compressed by the
compressor 15 to a high pressure. In the cooler 18 the
heat of compression is removed and the mixed refrigerant
is partially condensed. Cooling and partial condensation
of the mixed refrigerant may also be done in more than
one heat exchanger. In the separator 20, the mixed
refrigerant is separated into heavy mixed refrigerant and
light mixed refrigerant, which are the liquid product and
the vapour product, respectively.

Heavy mixed refrigerant is passed through the
conduit 42 to the second tube bundle 10, in which it is
sub-cooled. Light mixed refrigerant is passed through
conduit 43 to the third tube bundle 11, in which it is
liquefied and sub-cooled.

Sub-cooled heavy mixed refrigerant and light mixed
refrigerant are passed via the flow control valves 46 and
47 into the shell side 5, where they are allowed to
evaporate at a low pressure so as to remove heat from the
natural gas in the first tube bundle 7 and from the
refrigerants passing through the additional tube
bundles 10 and 11.

According to the present invention the production of
the liquefied natural gas product stream is controlled in
the following way.

First of all the temperature and the flow rate of the
liquefied natural gas product stream flowing through the
conduit 31 are measured. The temperature measurement
signal, referred to with reference numeral 50, is passed
to a temperature controller 52. The flow rate measurement
signal, referred to with reference numeral 55 is passed
to a first flow rate controller 56.

In addition, the flow rates of the heavy mixed
refrigerant and of the light mixed refrigerant passing
through conduits 44 and 45, respectively are measured.
The heavy mixed refrigerant flow rate measurement

5   signals, referred to with reference numerals 60a, 60b and
60c, are passed to a second flow rate controller 61, to a
first flow ratio controller 62 and to a second flow ratio
controller 63, respectively. The light mixed refrigerant
flow rate measurement signal, referred to with reference

10   numeral 65 is passed to a third flow rate controller 66.

The next step comprises controlling the flow rates of
the refrigerants. At first, the flow rate of one of the
refrigerants (the heavy mixed refrigerant, the light
mixed refrigerant or the total mixed refrigerant) is

15   selected to have an operator manipulated set point. In
the embodiment of Figure 1 the heavy mixed refrigerant is
selected to have an operator manipulated set point, which
is a set point signal referred to with reference
numeral 80 that is supplied to the second flow rate

20   controller 61.

The flow rate of the heavy mixed refrigerant is
controlled using (i) the operator manipulated set
point 80 for the flow rate of the heavy mixed refrigerant
and (ii) the measured flow rate 60a of the heavy mixed

25   refrigerant.

A difference between the measured flow rate 60a of
the heavy mixed refrigerant and its operator manipulated
set point 80 causes the second flow rate controller 61 to
generate an output signal 84 that adjusts the position of

30   the flow control valve 46. The adjustment is such that
the absolute value of the difference is below a
predetermined norm.

The flow rate of the light mixed refrigerant is
controlled using (i) the measured flow rates 60b and 65

35   of the heavy and the light mixed refrigerant and (ii) an

operator manipulated set point 81 for the ratio of the
flow rate of the heavy mixed refrigerant to the flow rate
of the light mixed refrigerant.

The first flow ratio controller 62 divides the
measured flow rate 60b of the heavy mixed refrigerant by
the operator manipulated set point 81 for the ratio of
the flow rates of heavy mixed refrigerant and light mixed
refrigerant to generate an output signal 85 that is the
dependent set point for the third flow rate
controller 66. Then a difference between the measured
flow rate 65 of the light mixed refrigerant and its
dependent set point 85 causes the third flow rate
controller 66 to generate a second output signal 86 that
adjusts the position of the flow control valve 47. The
adjustment is such that the absolute value of the
difference is below a predetermined norm. In an
alternative embodiment (not shown) a difference between
the ratio of the measured flow rate 60b of the heavy
mixed refrigerant to the measured flow rate 65 of the
light mixed refrigerant and the operator manipulated set
point 81 for this ratio, causes the first flow ratio
controller 62 to generate an output signal 85 that is the
dependent set point for the third flow rate
controller 66. Then a difference between the measured
flow rate 65 of the light mixed refrigerant and its
dependent set point 85 causes the third flow rate
controller 66 to generate a second output signal 86 that
adjusts the position of the flow control valve 47. The
adjustment is such that the absolute value of the
difference is below a predetermined norm.

In this way the flow rates of the heavy mixed
refrigerant and the light mixed refrigerants are
controlled.

Secondly the temperature of the liquefied natural gas
product stream is controlled. To this end, a dependent

set point for the ratio of the flow rate of the liquefied
natural gas product stream to the flow rate of one of the
refrigerants (in this case the heavy mixed refrigerant)
is determined such that the temperature of the liquefied
5   natural gas product steam is maintained at an operator
manipulated set point. The operator manipulated set point
for the temperature of the liquefied natural gas product
stream is a set point signal referred to with reference
numeral 90 that is supplied to the temperature
10   controller 52.

A difference between the temperature 50 of the
liquefied natural gas product stream and its operator
manipulated set point 90 causes the temperature
controller 52 to generate an output signal that is the
15   dependent set point 91 for the second flow ratio
controller 63. Using the measured flow rate 60c of the
heavy mixed refrigerant the second flow ratio
controller 63 generates an output signal 95 that is the
dependent set point for the flow rate of the liquefied
20   natural gas product stream. A difference between the
measured flow rate 55 of the liquefied natural gas
product stream and its dependent set point 95 causes the
first flow rate controller 56 to generate an output
signal 96 that adjusts the position of the flow control
25   valve 33. The adjustment is such that the absolute value
of the difference is below a predetermined norm.

In this way the flow rate of the liquefied natural
gas product stream is controlled in such a way that the
temperature of the liquefied natural gas product stream
30   is maintained at its operator manipulated set point.

An advantage of this control method is that the flow
rate of the liquefied natural gas product stream is
adjusted to maintain the temperature of the product
stream at its operator manipulated set point in the form
35   of trim control. Moreover, because the operator can

manipulate the set point 80 for the heavy mixed refrigerant flow rate and the set point 81 for the ratio, the available power of the driver 16 can be fully utilized.

It may be necessary to override the above-described temperature control. If that is the case, the above way of controlling the flow rate of the liquefied natural gas product stream is overridden by determining a dependent set point for the flow rate of the liquefied natural gas product stream such that the temperature of the liquefied natural gas is maintained at an operator manipulated set point. In this case, the temperature controller 52 works directly on the first flow rate controller 56.

There are two alternatives for controlling the flow rates of the refrigerants. In the first alternative, the flow rate of the light mixed refrigerant is selected to have an operator manipulated set point. The method then comprises generating a second output signal for adjusting the flow rate of the light mixed refrigerant using the operator manipulated set point for the flow rate of the light mixed refrigerant, and generating a first output signal for adjusting the flow rate of the heavy mixed refrigerant using (i) the measured flow rates of the heavy mixed refrigerant and of the light mixed refrigerant and (ii) an operator manipulated set point for the ratio of the flow rate of the heavy mixed refrigerant to the flow rate of the light mixed refrigerant.

In the second alternative the flow rate of the total mixed refrigerant is selected to have an operator manipulated set point. The method then comprises generating a first output signal for adjusting the flow rate of the heavy mixed refrigerant and a second output signal for adjusting the flow rate of the light mixed refrigerant using (i) the operator manipulated set point

for the flow rate of the total mixed refrigerant, (ii) the measured flow rates of the heavy and light mixed refrigerants and (iii) an operator manipulated set point for the ratio of the flow rate of the heavy mixed refrigerant to the flow rate of the light mixed refrigerant.

There are several alternatives for controlling the temperature of the liquefied natural gas product stream. In the first alternative, a dependent set point for the ratio of the flow rate of the liquefied natural gas product stream to the flow rate of the light mixed refrigerant is determined such that the temperature of the liquefied natural gas product stream is maintained at the operator manipulated set point. The method then comprises determining a dependent set point for the flow rate of the liquefied natural gas product stream using (i) the dependent set point for the ratio of the flow rate of the liquefied natural gas product stream to the flow rate of the light mixed refrigerant and (ii) the measured flow rate of the light mixed refrigerant.

In the second alternative a dependent set point for the ratio of the flow rate of the liquefied natural gas product stream to the flow rate of the total mixed refrigerant is determined such that the temperature of the liquefied natural gas product stream is maintained at the operator manipulated set point. The method then comprises determining a dependent set point for the flow rate of the liquefied natural gas product stream using (i) the dependent set point for the ratio of the flow rate of the liquefied natural gas product stream to the flow rate of the total mixed refrigerant and (ii) the measured flow rate of the total mixed refrigerant.

Reference is made to Figure 2, which shows a further alternative. Parts shown in Figure 2 that are identical to parts shown in Figure 1 are given the same reference

numerals. In this alternative embodiment, the ratio of the flow rate of the liquefied natural gas product stream to the flow rate of the heavy mixed refrigerant is not determined so as to control the temperature, but it is an operator manipulated set point 96, which is a set point signal supplied to a third ratio controller 97. The third ratio controller 97 generates a first output signal 98 using (i) the operator manipulated set point 96 for the ratio of the flow rate of the liquefied natural gas product stream to the flow rate of the heavy mixed refrigerant and (ii) the measured flow rate 60c of the heavy mixed refrigerant. The temperature controller 52 generates a second output signal 91 using the operator manipulated set point 90 for the temperature and the measured temperature 50. The output signals are each multiplied with a separate weighting factor and the weighted signals are then added in adder 99 to obtain the dependent set point 95 for the flow rate of the liquefied natural gas product stream.

Alternatively, the flow rate of the light mixed refrigerant is used or the flow rate of the total mixed refrigerant.

Using both the ratio and the temperature to control the flow rate of the liquefied natural gas product stream is particularly suitable, when the flow rate measurement is not too accurate. When the flow rate measurement signal is not accurate, the weighting factor applied to the first output signal 98 can have a low value.

Suitably, the liquefaction plant is provided with means (not shown) to measure the power delivered by the driver 16, which means can override the operator manipulated set point 80 for the flow rate of the heavy mixed refrigerant if the power delivered by the driver 16 has reached a predetermined maximum value. The override ensures that the operator manipulated set point 80 for

the flow rate of the heavy mixed refrigerant can no
longer be increased. Alternatively, when either the light
mixed refrigerant or the total mixed refrigerant has an
operator manipulated set point, the means can override
one of the latter set points.

Suitably, the driver 16 is a gas turbine, and the
temperature of the gas at the exhaust of the gas turbine
is used as a measure of the power of the driver.

In the embodiment shown in Figure 1, the first flow
ratio controller 62 controls the dependent set point 85
of the third flow rate controller 66 using the measured
flow rate of the heavy mixed refrigerant and the operator
manipulated set point 80 for the ratio between the flow
rate of the heavy mixed refrigerant to the flow rate of
the light mixed refrigerant. Alternatively, this ratio
can be the ratio of the ratio of the flow rate of the
heavy mixed refrigerant to the flow rate of the total
mixed refrigerant or the ratio of the flow rate of the
light mixed refrigerant to the flow rate of the total
mixed refrigerant.

Reference is now made to Figure 3, which shows
schematically an alternative embodiment of the present
invention, wherein the liquefied natural gas product
stream is obtained by adding the liquefied natural gas
leaving two identical heat exchangers arranged in a
parallel line-up. Parts shown in Figure 3 that are
identical to parts shown in Figure 1 are given the same
reference numerals, and, for the sake of clarity, we have
omitted from Figure 2 the compressor, the separator and
the light mixed refrigerant flow path.

The plant now comprises two substantially identical
heat exchangers, 2 and 2'. In the heat exchangers 2 and
2' the natural gas passes through the first tube
bundles 7 and 7', where it is in indirect heat exchange
with expanded heavy mixed refrigerant and expanded light

mixed refrigerant. Natural gas leaves the first heat
exchanger 2 through conduit 100, and it leaves the second
heat exchanger through conduit 100'. The two liquefied
gas streams are combined to obtain the liquefied natural
5   gas product stream that flows through conduit 31.

        The flow rates of the heavy and light mixed
refrigerants for each of the heat exchangers 2 and 2' are
controlled in the way already discussed with reference to
Figure 1. The temperature and the flow rate of the
10   liquefied natural gas product stream are controlled by
the method as described in the above with reference to
Figures 1 and 2.

        Controlling the temperature and the flow rate of the
liquefied natural gas product stream is now discussed in
15   more detail. A difference between the temperature 50 of
the liquefied natural gas product stream and its operator
manipulated set point 90 causes the temperature
controller 52 to generate a set point signal that is the
dependent set point 91 for the second flow ratio
20   controller 63. Using the measured flow rate 60c'' of the
heavy mixed refrigerant the first flow ratio controller
generates a set point signal 95 that is the dependent set
point for the first flow rate controller 56. A difference
between the measured flow rate of the liquefied natural
25   gas product stream 55 and its dependent set point 95
causes the first flow rate controller 56 to generate an
output signal 96 that adjusts the position of the flow
control valve 33. The adjustment is such that the
absolute value of the difference is below a predetermined
30   norm.

        Here the flow rate of the heavy mixed
refrigerant 60c'' is the sum of the flow rates 60c and
60c'. It will be understood that in place of the flow
rate of the heavy mixed refrigerant, one can use also the
35   flow rate of the light mixed refrigerant or the flow rate

of the total mixed refrigerant.

In order to balance the flow of liquefied natural gas through the conduits 100 and 100', these conduits are provided with flow control valves 103 and 103'. The flow rates in the conduits 100 and 100' are measured, and the measurement signals 105a and 105a' are supplied to flow controllers 106 and 106'. Moreover measurement signals 105b and 105b' are supplied to a further flow controller 110.

The flow control valves 103 and 103' are both put in the fully open position, and the further flow controller 110 determines which of the two measured flow rates, 105b or 105b' is the smallest. Let the flow rate 105b be the smallest. Then the flow control valve 103 is kept at its fully open position, and a dependent set point 122 for the flow rate of the liquefied natural gas flowing through flow control valve 103' is determined. The dependent set point 122 is so determined that that the flow rate 105b' is equal to the flow rate 105b.

A difference between the measured flow rate 105a'and its set point 122 generates an output signal 123 that adjusts the position of the control valve 103'. The adjustment is such that the absolute value of the difference is below a predetermined norm.

In a further embodiment, an imbalance in the flow rates of one of the refrigerant flows is also taken into account. As an example the flow rate of the heavy mixed refrigerant is taken. These flow rates 60d and 60d' are supplied to the further flow controller 110.

The flow control valves 103 and 103' are both put in the fully open position, and the further flow controller 110 determines which of the two measured flow rates, 105b or 105b' is the smallest. Let now the flow rate 105b' be the smallest. Then the flow control

valve 103' is kept at its fully open position, and a
dependent set point 120 for the flow rate of the
liquefied natural gas flowing through flow control
valve 103 is determined. To determine the dependent set
5   point 120, the further flow controller 110 determines (i)
the ratio of the measured flow rate 105b of the liquefied
natural gas leaving the first heat exchanger to the
measured flow rate 60d of the heavy mixed refrigerant
supplied to the first heat exchanger 2 and (ii) the ratio
10   of the measured flow rate 105b' of the liquefied natural
gas leaving the second heat exchanger 2' to the measured
flow rate 60d' of the heavy mixed refrigerant supplied to
the second heat exchanger 2'. And then the quotient of
the two ratios is compared with an operator manipulated
15   set point for this quotient, which operator manipulated
set point is set point signal 125 supplied to the further
flow controller 110.

A difference between the measured flow rate 105a and
its set point 120 generates an output signal 126 that
20   adjusts the position of the control valve 103. The
adjustment is such that the absolute value of the
difference is below a predetermined norm.

Instead of using the ratio with the flow rate of the
heavy mixed refrigerant 60d and 60d', the ratio can also
25   be obtained using the flow rate of the light mixed
refrigerant or the flow rate of the total mixed
refrigerant.

In a further embodiment, the flow rates of the
liquefied natural gas from the heat exchangers 2 and 2'
30   are balanced using the temperatures of these streams. To
this end a temperature controller (not shown) compares
the temperature of the liquefied natural gas in
conduit 100 to the temperature of the liquefied natural
gas in conduit 100'. The temperature controller first
35   determines the stream having the highest temperature, and

then adjust the set point for the flow controller of that stream, so as to decrease the temperature of that liquefied natural gas stream.

In the above described embodiments of the invention, the output signals for adjusting the flow rates of the refrigerants are determined from the (i) the measured flow rates of the refrigerants and (ii) an operator manipulated set point for the ratio of the flow rate of the heavy mixed refrigerant to the flow rate of the light mixed refrigerant. However instead of using the measured flow rate of one of the other refrigerants, the operator manipulated set point for that refrigerant can be used. And the same applies to determining the dependent set point for the flow rate of the liquefied natural gas product stream.

In order to prevent large variations in the temperature of the liquefied natural gas product stream a lag can be introduced in the signal 95 that is the set point for the flow rate of the liquefied natural gas product stream.

The flow rates are mass flow rates and they are suitably measured upstream a flow control valve. Also the temperature of a flow is suitably measured upstream a flow control valve.